Impact of Diabatic Processes on 4-Dimensional Variational Data Assimilation with the Global Spectral Model at NCEP/NOAA

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Introduction

- Physical processes play important roles in the atmospheric evolution by modifying the local budget of mass, momentum and energy by adding sources and/or sinks.
- In a discretized numerical system, many important physical processes such as turbulence and convection are in sub-grid scales and incorporated into NWP models through a parameterization approach.
- Parameterizations use the grid-scale resolvable information to simulate the mean effect of sub-grid processes in a grid-box by deriving characteristic parameters.
- Parameterized physical processes are turned on or off when a certain characteristic parameter crosses a threshold, i.e., “on- off” switches exist in parameterizations.
- Both the model solution and the cost function of a diabatic model including parameterized physics may be discontinuous due to the “on-off” switches in parameterizations.
- Discontinuities in a diabatic assimilation model may render the minimization in 4DVAR to fail.

NCEP global spectral model (1995 version)

- Hydrodynamics:
  - Prognostic variables: vorticity (ζ), divergence (D), virtual temperature (T), specific humidity (q) and surface pressure (p).
  - Governing equations: tendency equations of ζ, D, T, q and ln(p).
  - Resolution: 62 waves (not including the zonal mean) in horizontal domain and 28 vertical levels.
  - The dynamical core includes horizontal diffusion (diff coeff: α_{HD}) and time filtering (filtering coeff: α_A) at each time-step integration.
- Parameterizations:
  - Large-scale precipitation and Shallow convection (Betts et al. 1986).
  - A simplified (one-type cloud, Pan et al. 1995) Arakawa-Schubert (1974) cumulus scheme.
  - A nonlocal vertical diffusion scheme (Hong and Pan 1996).
  - Gravity-wave drag (Pierrehumbert 1986).
  - Boundary and surface processes (Monin-Obukhov similarity theory and a two-layer soil model).
  - Long-wave and short-wave radiation are kept constant in 6-h assim window.

A cost function measuring forecasting spectral errors

- ✓ **NCEP re-analysis data set with 6-hour interval starting from 00 UTC on 1 October 1995, and the state vector is represented by the spectral coeffs:**

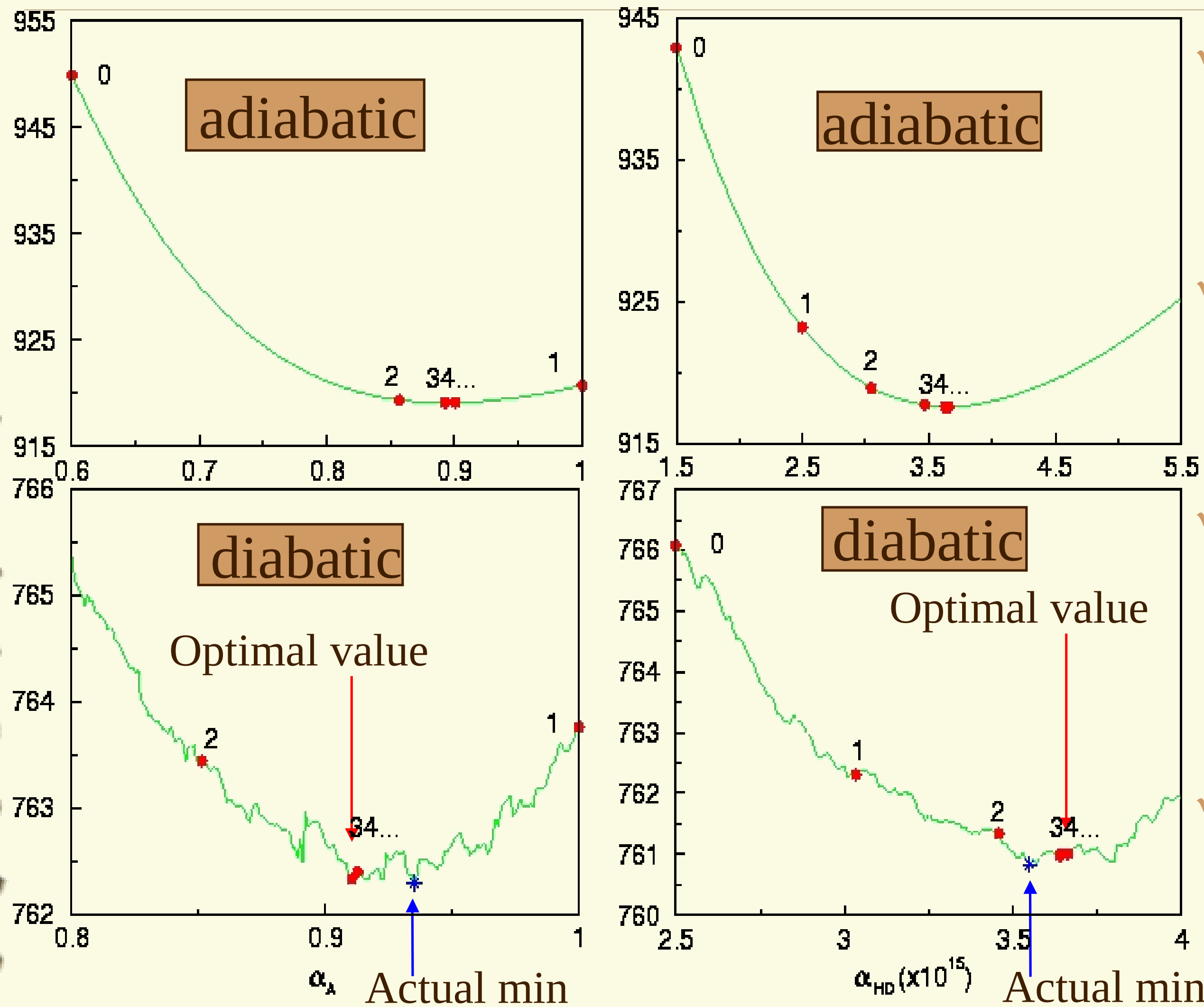
  $\mathbf{x}=(\zeta_{m,n}, \mathbf{D}_{m,n}, \mathbf{T}_{m,n}, \mathbf{q}_{m,n}, \mathbf{p}_{m,n})^T$, m/n is Fourier/Legendre sum index.

- ✓ **Use 6-hour assimilation window to define the cost function:**

  $J(\alpha)=1/2\langle \mathbf{W}(\mathbf{x}^{6h}-\mathbf{x}^{a}), (\mathbf{x}^{6h}-\mathbf{x}^{a})\rangle$

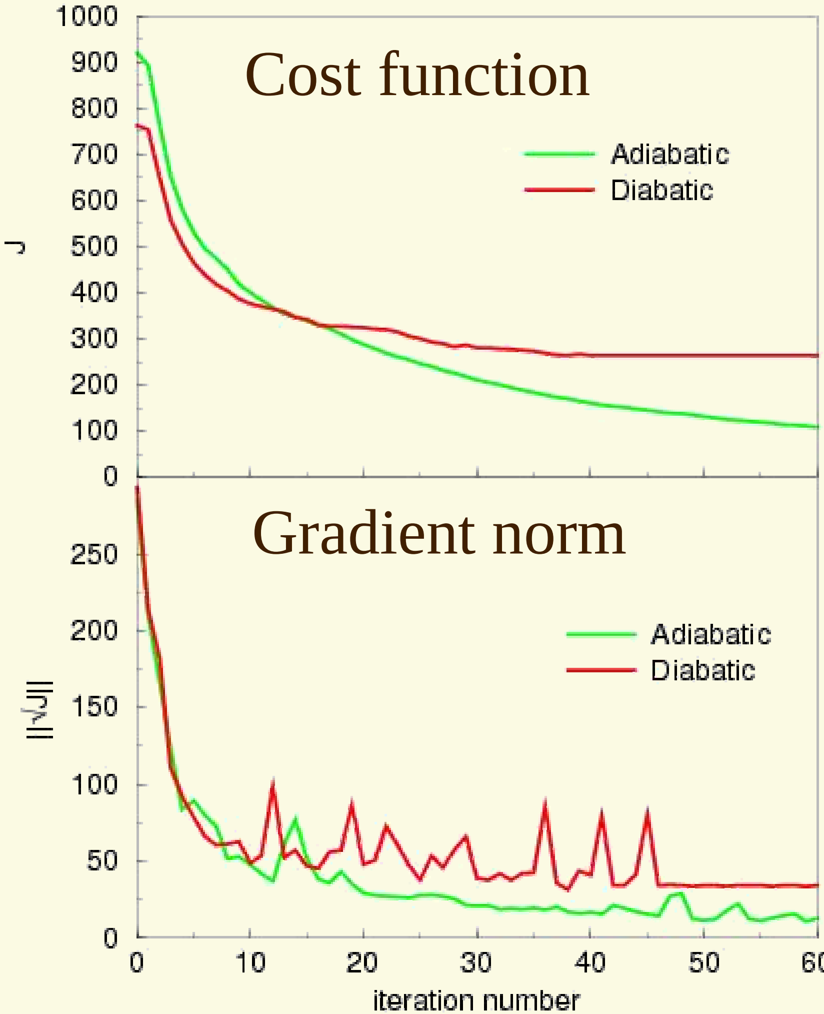
  - $\langle , \rangle$: dot product, l_2 Euclidean norm, of two vectors.
  - α: control variable vector, may include initial conditions and any adjustable parameters.
  - $\mathbf{x}^{6h}$: 6-hour model forecast state vector starting from initial state at 00 UTC on 10/01/95.
  - $\mathbf{x}^{a}$: re-analysis state at 06 UTC on 10/01/95.
  - **W**: a diagonal weighting matrix: the inverse of the absolute value of maximal 6-hour differences of the variable spectral coefficients for each zonal wavenumber.

Jagged behavior of a diabatic cost function leads to minimization problems: 1-d cases



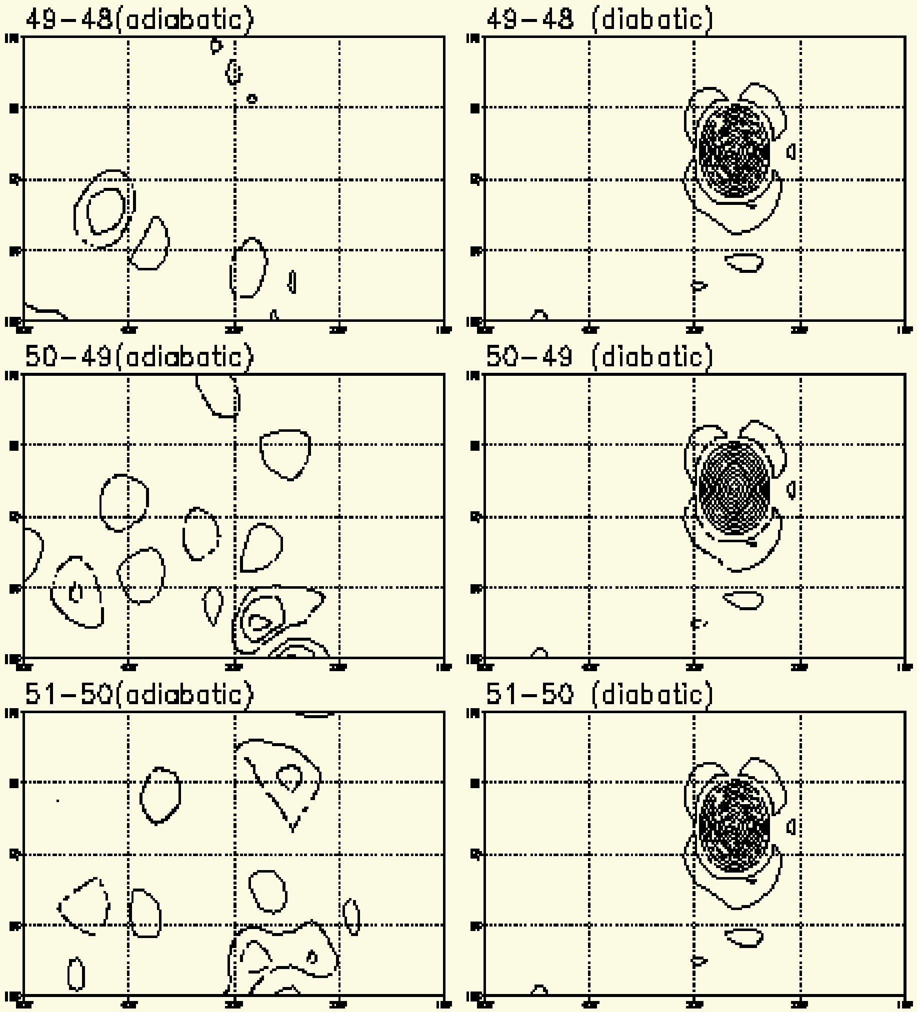
- Evaluate J using 0.001 α_A and 0.001x10^{16} α_{HD} interval.
- Optimize α_A and α_{HD} using L-BFGS algorithm.
- In adiabatic cases optimal value is consistent with evaluated min.
- In diabatic cases optimal value is a local min.

Jagged behavior of a diabatic cost function leads to minimization problem: multi-d cases



- The adiabatic forward model and adjoint carry “ adiabatic 4DVAR.” and the diabatic forward model and adjoint carry “ diabatic 4DVAR .”
- At the initial stage of minimization, the diabatic J is smaller than the adiabatic J since a diabatic model simulates the atmospheric state more realistically.
- During the first 10 iterations, both adiabatic and diabatic J’s and their gradient norms are rapidly reduced by 62% and 90% (adiabatic J and $\|\nabla J\|$), 54% and 83% (diabatic J and $\|\nabla J\|$).
- The rate of decrease of the diabatic cost function slows after 10 iterations and the diabatic J and $\|\nabla J\|$ are even unchanged after 45 iterations.
- 60 iterations of minimization reduce the adiabatic J and $\|\nabla J\|$ by 88% and 95%, but only 66% and 88% for diabatic J and $\|\nabla J\|$.

Continuous (adiabatic) and discontinuous (diabatic) adjustment in minimization



- The minimization using adiabatic model and adjoint continuously adjusts the relatively small scale flows after 30 iterations.
- In diabatic minimization, the adjusted state exhibits a switching characteristic back and forth between two states due to discontinuities in parameterizations after 30 iterations.
- **Question**: How do scales impact the diabatic minimization?

Decrease of the cost functions of different scale flows in minimization: Partition of J in spectral domains

- The contribution for total J from each wavenumber (index: $I_{m,n}$) is

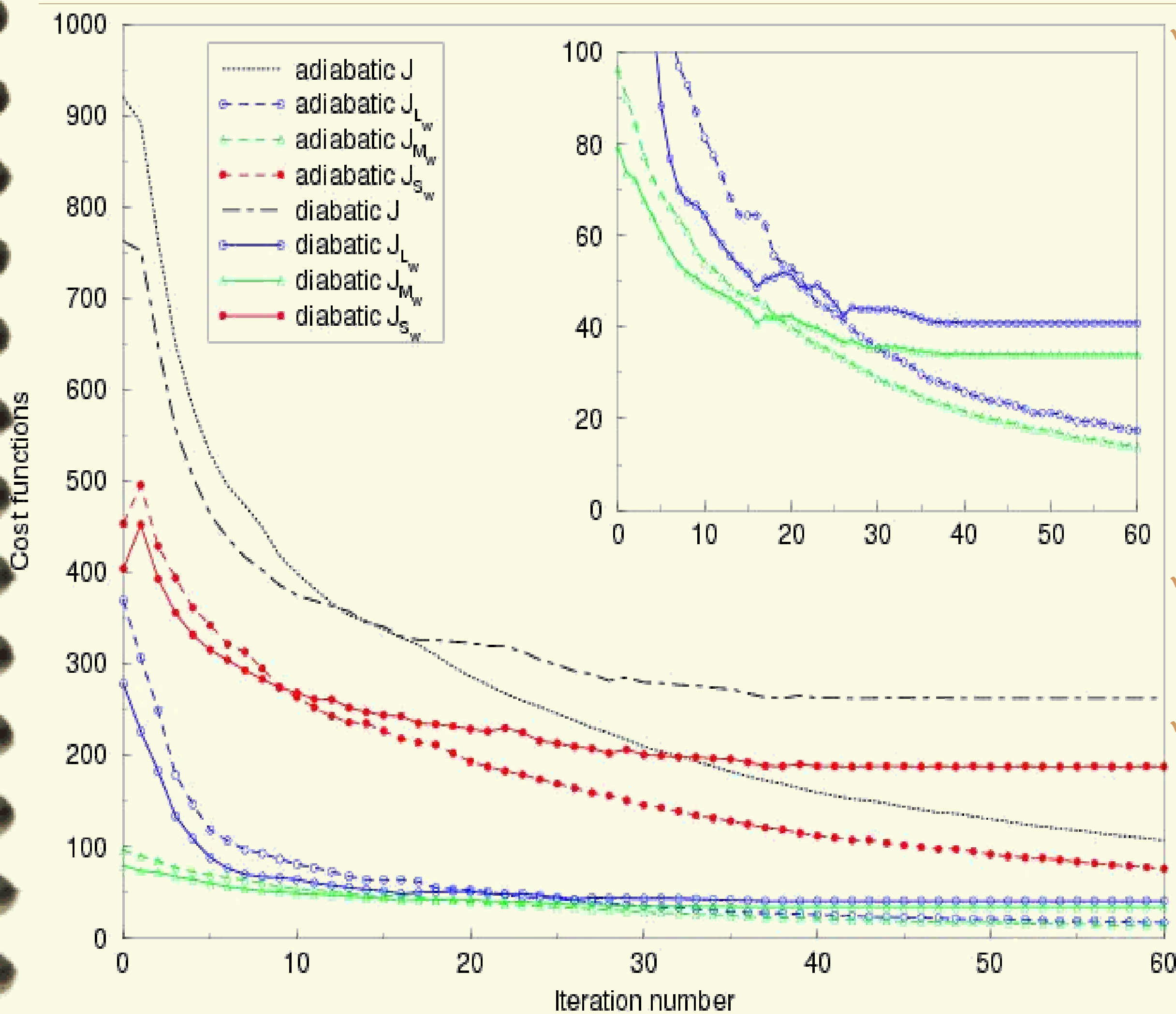
$$J_{I_{m,n}}=1/2\{w_D(m)\Sigma_k[(e_D)_{m,n}]_k^2+w_\zeta(m)\,\Sigma_k[(e_\zeta)_{m,n}]_k^2+ w_T(m)\,\Sigma_k[(e_T)_{m,n}]_k^2+w_q(m)\,\Sigma_k[(e_q)_{m,n}]_k^2+ w_p(m)\,[(e_p)_{m,n}]^2\}.$$

- Re-grouping by spectral domains:

$$J(\alpha)=\Sigma_{I_{m,n}} J_{I_{m,n}} = J_{L_w}+J_{M_w}+J_{S_w}$$
$$J_{L_w}=\Sigma_{m=0}^{M1}\Sigma_{n=m}^{M1}(J_{I_{m,n}})$$
$$J_{M_w}=\Sigma_{m=0}^{M2}\Sigma_{n=M1}^{M2}(J_{I_{m,n}})$$
$$J_{S_w}=\Sigma_{m=0}^{M}\Sigma_{n=M2}^{M}(J_{I_{m,n}}).$$

- Pick up M_1=10, M_2=20 to form J_{L_w}, J_{M_w} and J_{S_w} to represent the contribution of the "Long-wave," "Middle-wave" and "Short-wave" flows for the total cost function J.

Decrease of J_{Lw}, J_{Mw} and J_{Sw} in the L-BFGS minimization



- At the beginning stage (say before 10), J_{Lw} decreases at the fastest rate in both adiabatic (78%) and diabatic (77%) cases and diabatic J_{Lw}, J_{Mw} and J_{Sw} have almost the same rate of decrease as the corresponding adiabatic ones.
- Decrease of diabatic J_{Lw} slows down during iteration 10-30
- After 30 iterations, the diabatic J_{Lw}, J_{Mw} and J_{Sw} are unchanged while the adiabatic J_{Sw} has the fastest decrease rate.

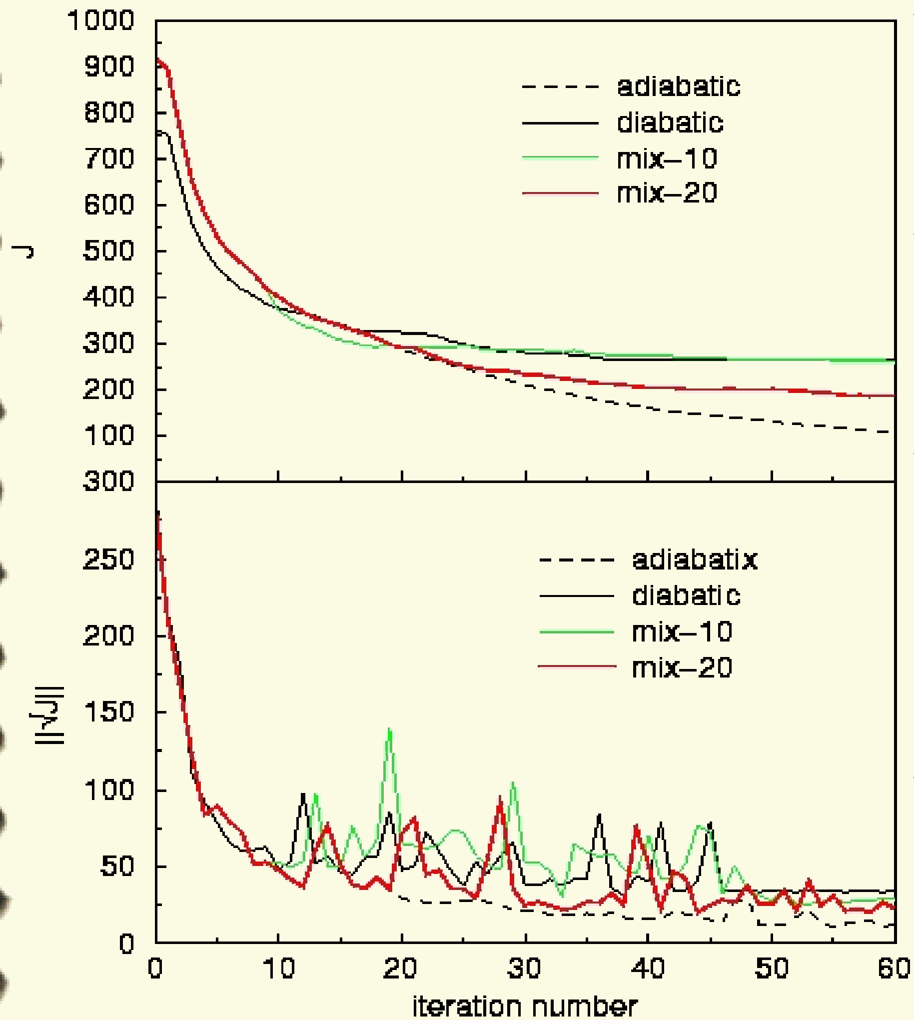
Summary for decrease of cost functions in different spectral domains (J_{Lw}, J_{Mw} and J_{Sw})

- At the beginning stage the minimization mainly adjusts larger scale flows and discontinuities in parameterizations are not important.
- As iterations proceed, the adjustment of the relatively small scales increases and discontinuities in parameterizations have an increasing impact on the minimization.
- Iteration 10-30 is a transition period in which the diabatic J_{Sw} starts to be locked by discontinuities and the decrease of the diabatic J_{Lw} and J_{Mw} is impacted by discontinuities due to the feedback on the large-scale flows from small scales.
- In the transition period, there exists a critical scale arrange which easily causes the minimization locked.
- After 30 iterations, the adjustment focuses on relatively small scales and the diabatic cost functions in all wavenumber domains (J_{Lw}, J_{Mw} and J_{Sw}) are unchanged due to the fact that the minimization is locked by discontinuities.

A mixed 4DVAR implementation scheme: **Experiment design**

- ✓ Use the adiabatic forward model and adjoint to first adjust the large-scale flows.
- ✓ Switch to the diabatic forward model and adjoint to adjust relatively smaller scales after a while.
- ✓ If the switch occurs after the minimization has gone through the critical scale arrange which easily causes the minimization locked, the mixed 4DVAR implementation scheme is expected to be able to lessen the impact of discontinuities on minimization.
- ✓ The mixed 4DVAR scheme is also expected to be cheaper computationally because of the calls of adiabatic forward model and adjoint at the beginning stage.

Numerical results: Decreases of J and ||∇J||

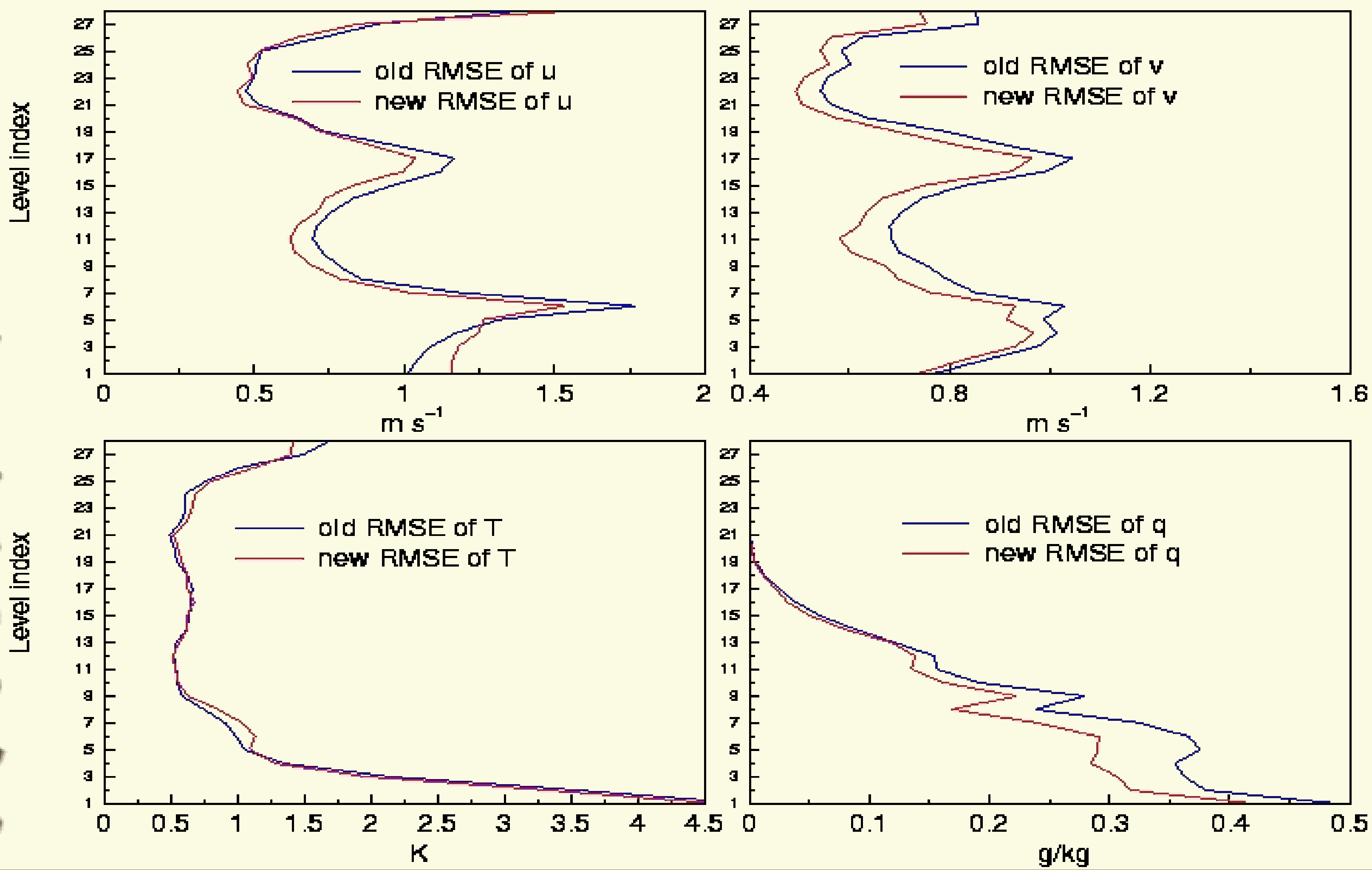


- The adiabatic adjustment of 20 iterations (mix-20) causes that the minimization has gone through some critical scale arrange.
- Mix-20 (new scheme) leads to that the cost function and its gradient norm decrease 29% and 35% more.
- The adiabatic adjustment of 10 iterations (mix-10) is insufficient for minimization to move to relatively small scale adjustment for lessening the impact of discontinuities.
- The adiabatic adjustment of 30 iterations (mix-30) is too much and leads to failure of minimization.

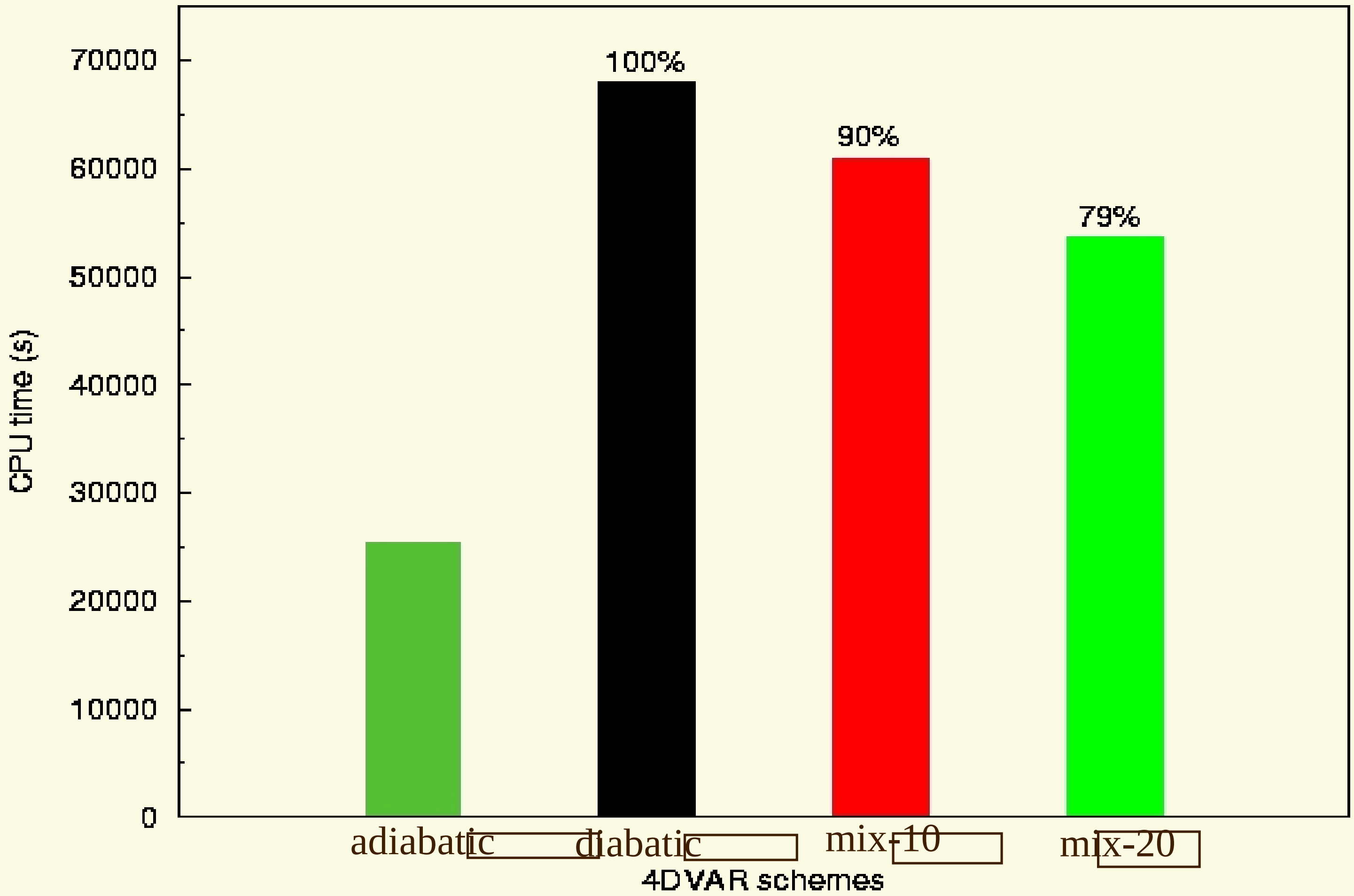
Numerical results: Comparison of RMS errors in New(mix-20)/Old scheme

Forecast leading time (hour)	RMS errors									
	Total		u(m/s)		v(m/s)		T_v(K)		Q(0.1g/kg)	
	old	new	old	new	old	new	old	new	old	new
06	0.749	0.726	0.897	0.856	0.785	0.712	1.066	1.059	1.437	1.177
12	1.524	1.518	2.306	2.295	2.544	2.548	1.770	1.748	3.069	3.028
18	1.678	1.675	2.599	2.588	2.716	2.737	2.075	2.052	3.693	3.648
24	1.776	1.772	2.763	2.759	2.825	2.834	2.291	2.267	4.143	4.083
30	1.858	1.856	2.968	2.972	2.947	2.949	2.377	2.358	4.447	4.402
36	1.924	1.918	3.116	3.104	3.017	3.025	2.484	2.462	4.686	4.647
42	2.072	2.069	3.409	3.402	3.163	3.162	2.795	2.780	5.050	5.033
48	2.147	2.140	3.605	3.589	3.301	3.296	2.830	2.814	5.541	5.535

Numerical results: RMSE vertical distribution of new/old scheme at 48-hour



Numerical results: Reduction of mixed scheme's CPU



Summary and future work

- During the minimization, the cost function of the diabatic model was locked in a shallow local minimum due to discontinuities in parameterizations while the cost function of the adiabatic model converged to a global minimum.
- At the beginning stage (first 10 iterations) the minimization mainly adjusts larger scale flows in which discontinuities in parameterizations play little role. As iteration proceeds, the adjustment gradually moves to the relatively small scales around 20 iterations. During this transition period, there exists a critical scale arrange that causes the diabatic cost function to stick in a local minimum in stead of continuously decreasing toward a deeper minimum.
- A mixed 4DVAR implementation scheme first uses the adiabatic model and adjoint to adjust large-scale flows. When the adjustment of minimization has gone through the critical scale arrange, the mixed scheme switches to the diabatic model and adjoint to adjust relatively small scales. The mixed scheme reduces the diabatic cost function and the norm of gradient by 29% and 35% more respectively for 60 iterations and reduces CPU time by 21%. The resulting optimal initial conditions from the new scheme improve the short-range forecast skill with 48-hour statistics.
- The mixed 4DVAR scheme only lessens the effect of parameterization discontinuities in the diabatic minimization but gets free of the problem. The best switch from adiabatic adjustment to diabatic adjustment for reducing the diabatic cost function may be case-dependent and need further study.
- Bundle method and “generalized” approach may be another potential alternative.

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Question?